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A NEW SYSTEM FOR MEASUREMENT OF LOW FREQUENCY RADIO TRANSMITTING ANTENNA PARAMETERS IN NEAR REAL TIME

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ABSTRACT

Fixed site very low frequency (VLF) and low frequency (LF) transmit antenna systems are used as the primary means of communication to submarines at sea. Until now there has not been a system to measure important antenna parameters on these low frequency transmit antennas in near real time while the antenna is being driven by frequency shift modulation. This paper describes a new system which can be used to measure several important antenna and tuning system parameters on these transmit antennas while the antennas are in normal operation. The measurements are made by sampling and processing the antenna voltage and current signals to calculate the antenna system resistance, capacitance, inductance, voltage, current and power which can then be displayed and stored on a personal computer. All of these measurements are made while the antenna is being driven by FSK or MSK signals. The paper includes a model of a typical low frequency transmit antenna as well as the associated equations. The response of the antenna system to frequency shift keying signals is then presented. In addition, the algorithms, hardware, and software used by the measurement system, called the VLF/LF antenna monitor system (AMOS), are discussed along with a summary of results obtained during initial testing of the AMOS system.

1.0 – BACKGROUND

Very low frequency (VLF, 3 to 30 KHz) and low frequency (LF, 30 to 300 KHz) radio systems are used as the primary radio communication link between submarines operating at sea and shore based transmit facilities. These frequency ranges are used for a variety of reasons including significant sea water penetration of electromagnetic energy, stable propagation, and low atmospheric attenuation [1]. Due to the very long wavelength of radio waves at these low frequencies (2000 to 15000 meters in the operating range normally used for submarine communication) designing and building efficient transmitting antenna systems in these frequency ranges is a difficult problem. Existing fixed site transmit antennas operating in this range are normally electrically short (much less than a wavelength) but physically very large and difficult to operate and monitor. Most of the antennas used in this operating range are top loaded vertical monopoles which can be characterized in the frequency band around the operating frequency by three primary lumped sum circuit parameters, the antenna system capacitance, Cas, inductance, Las, and gross resistance, Rg [1].

Figure 1 shows an electrical equivalent circuit model for a typical VLF or LF top loaded monopole type transmitting antenna. In this figure the transmitter is represented by an ideal voltage source, Vtr, and the impedance, Ztr, which models the reactance and losses in the transmitter system. The antenna and associated tuning system is represented by the three passive components Rg, Las, and Cas. The capacitive component in the antenna circuit, Cas, comes primarily from the antenna top hat configuration due to the capacitance between the top hat and the ground screen.

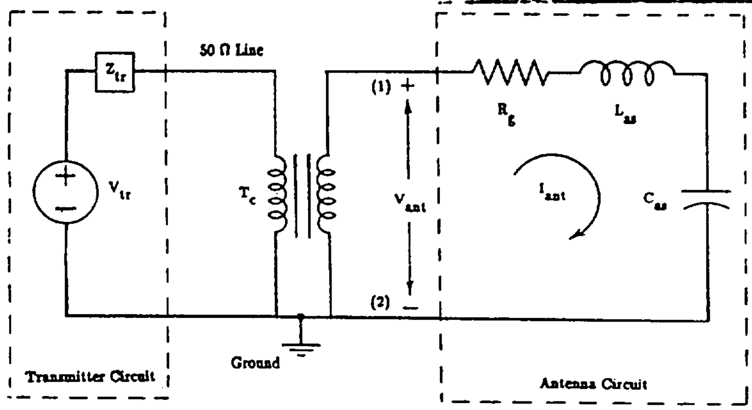

Figure 1 – Antenna System Equivalent Circuit

There will also be some contribution to Cas from stray capacitances between the tower and ground and the cabling and upleads to ground. The inductive component, Las, comes from the stray inductance in the cabling combined with an added series inductance, usually in the form of a helix and or a variometer, which is used to tune the antenna to the desired operating frequency. The resistive component, known as the antenna system resistance or gross resistance and labeled Rg, is due to series ohmic losses in the transmission line, the ground screen, and the antenna structure, combined with the radiation resistance of the antenna. To simplify the analysis of the antenna and associated tuning system the capacitive, inductive, and resistive components can be combined to form the equivalent lumped sum parameters Cas, Las, and Rg. The resultant circuit, as shown in figure 1, is a simple RLC series circuit which has been thoroughly analyzed and is described in almost every circuit analysis text.

The transmitter is coupled to the antenna system through a transmission line and some type of coupling network. In LF systems an impedance matching transformer is normally used for this network. This transformer, shown in figure 1 as Tc, matches the 50 ohm transmission line to the low impedance (≈ 1 Ohm) load of the antenna and tuning system. Most LF systems operate with antenna input power levels of from 30 to 50 KW so this transformer needs to be able to handle at least this much power. In VLF systems, which normally operate at a much higher power level, the input power can be anywhere from 100 KW to over 1 MW. Due to the higher power rating required by VLF systems, a tuning variometer is typically used to provide the coupling between transmitter and antenna systems. This paper discusses primarily LF antennas since LF systems have been used for the initial implementation of the AMOS system. Therefore, the coupling network is assumed to be the transformer as shown in figure 1.

Knowledge of these three primary antenna system parameters, Cas, Las, and Rg and their variation over time is extremely useful in both operating the transmit system and diagnosing problems. For example, a failure in a component such as a tower guy wire or base insulator can be recognized by a change in the gross resistance, Rg, or capacitance, Cas.

Operationally, knowledge of antenna voltage, current, and phase angle between the two can be used to optimally tune the antenna system. Since most of these systems are physically large and difficult to examine in normal operation or in the event of component failure, a tool that is capable of measuring these antenna parameters remotely during normal operation is very desirable

2.0 – MEASUREMENT SYSTEM REQUIREMENTS

In general it is not difficult to measure the antenna parameters previously described for this type of series RLC circuit. The most practical way is to drive the antenna system with a single frequency sinusoidal signal and measure the magnitude of the voltage, current, and phase angle between the two on the secondary side of the impedance matching transformer (Vant and Iant in figure 1). We can write the steady state voltage and current signals as,

$$\mathrm{Vant}_i(t) = \mathrm{Vm}_i \cdot \mathrm{Cos}(\omega_i t) \qquad (1)$$

$$\mathrm{Iant}_i(t) = \mathrm{Im}_i \cdot \mathrm{Cos}(\omega_i t - \varphi_i) \qquad (2)$$

Where,

ω_i – ith radian frequency at which voltage, current, and phase measurements are made

$\mathrm{Vant}_i(t)$ – Voltage at antenna feed point at frequency ω_i

$\mathrm{Iant}_i(t)$ – Current at antenna feed point at frequency ω_i

Vm_i – Magnitude of $\mathrm{Vant}_i(t)$ at frequency ω_i

Im_i – Magnitude of $\mathrm{Iant}_i(t)$ at frequency ω_i

φ_i – Phase Angle between $\mathrm{Vant}_i(t)$ and $\mathrm{Iant}_i(t)$ at frequency ω_i (Impedance Phase Angle)

From these measurements the antenna resistance and reactance $X(\omega_i)$ at the ith measurement frequency can be calculated as,

$$\mathrm{Rg} = \frac{\mathrm{Vm}_i}{\mathrm{Im}_i} \cdot \mathrm{Cos}(\varphi_i) \qquad (3)$$

$$X(\omega_i) = \frac{\mathrm{Vm}_i}{\mathrm{Im}_i} \cdot \mathrm{Sin}(\varphi_i) \qquad (4)$$

It is assumed that the antenna resistance, inductance, and capacitance are not frequency dependent in a band of several hundred hz around the operating frequency. The reactance, however, is always a frequency dependent parameter. If measurements are made at two different frequencies around the operating frequency, Cas and Las can be obtained by solving the simultaneous reactance equations,

$$X_1 = \omega_1 \cdot \mathrm{Las} - \frac{1}{\omega_1 \cdot \mathrm{Cas}} \qquad (5)$$

$$X_2 = \omega_2 \cdot \mathrm{Las} - \frac{1}{\omega_2 \cdot \mathrm{Cas}} \qquad (6)$$

From these fundamental parameters other desired antenna system parameters and operating values can be calculated including the impedance, reactive power (VoltAmperes), and real power (Watts). Therefore, it is desired that any measurement system be capable of measuring directly or calculating Vm, Im, and φ or some function of φ as a function of time at two different frequencies.

3.0 – CHARACTERISTICS OF ANTENNA VOLTAGE AND CURRENT DURING NORMAL OPERATION

In normal operation, LF antenna systems use some sort of frequency shift keying, either FSK (Frequency Shift Keying) or on some newer systems MSK (Minimum Shift Keying). Either one of these systems is characterized by antenna voltage signals Vant(t) that remain constant in frequency for time periods that are integer multiples of the underlying baseband digital data signal. If we define the fundamental time period as Tb, then at each successive time period t, where $k \cdot Tb < t < (k+1) \cdot Tb$ and k is any positive integer, the voltage signal will either remain at the previous instantaneous frequency or change to the other keying frequency with equal probability.

If we define the antenna voltage signal Vant as the input to the antenna circuit and the corresponding antenna current Iant as the output, then the antenna circuit represents a linear system transforming the voltage signal to produce the current signal as an output. At each transition time in the input Vant, the signal will either remain at the same frequency or change to the other frequency with equal probability. Each time the frequency changes the current signal responds by transiting to a new steady state condition with respect to the voltage signal at the new frequency. Depending on the Q of the circuit, the current may or may not reach a steady state condition before the next frequency transition takes place. If the current signal does reach a steady state condition then the voltage, current, and phase angle can be measured and the desired antenna parameters described previously can be calculated. Since the underlying modulation is assumed to be FSK or MSK, the underlying signal consists of only two different frequencies. If we call these two frequencies the high and low frequencies, the measurement problem becomes one of determining when the antenna circuit has reached a steady state condition, measuring the voltage and current, and determining whether the driving signal is at the high or low frequency.

4.0 – CALCULATING FUNDAMENTAL PARAMETERS

The desired fundamental antenna parameters are Vant, Iant, and φ. Assuming the antenna circuit is in a steady state condition these parameters can be determined by sampling the voltage and current waveforms and processing the samples. We can write the sampled versions of voltage and current from equations 1 and 2 as,

$$\mathrm{Vant}_i[j\mathrm{Ts}] = \mathrm{Vm}_i \cdot \mathrm{Cos}(\omega_i j\mathrm{Ts}) \qquad (7)$$

$$\mathrm{Iant}_i[j\mathrm{Ts}] = \mathrm{Im}_i \cdot \mathrm{Cos}(\omega_i j\mathrm{Ts} - \varphi_i) \qquad (8)$$

Where,

j – Integer sample index
Ts – Sample period defined as 1/sampling rate
$\mathrm{Vant}_i[j\mathrm{Ts}]$, $\mathrm{Iant}_i[j\mathrm{Ts}]$ – Sampled voltage and current signals

From the samples we can approximate Vm and Im as

$$\hat{\mathrm{Vm}}_i = \left(\frac{2}{k} \cdot \sum_{j=1}^{k} \mathrm{Vant}_i^2[j\mathrm{Ts}] \right)^{1/2} \qquad (9)$$

$$\hat{\mathrm{Im}}_i = \left(\frac{2}{k} \cdot \sum_{j=1}^{k} \mathrm{Iant}_i^2[j\mathrm{Ts}] \right)^{1/2} \qquad (10)$$

Where,

$\hat{Vm}_i$ – Calculated approximation of Vm_i

$\hat{Im}_i$ – Calculated approximation of Im_i

k – Integer number of samples which spans an integer number of half cycles of the sampled signal

The cosine of the phase angle φ can then be approximated as,

$$\hat{Cos}(\varphi_i) = \frac{2}{\hat{Vm}_i \cdot \hat{Im}_i \cdot k} \cdot \sum_{j=1}^{k} (Vant_i[jTs] \cdot Iant_i[jTs]) \quad (11)$$

For the linear circuit shown in figure 1 the phase angle φ will range between +90 degrees and –90 degrees or lie in the first and fourth quadrants in a cartesian coordinate system. The calculation of the cosine of φ presents an ambiguity problem because the cosine function is positive in both the first and fourth quadrants. This effectively limits the calculation in (11) to the determination of a function of the magnitude of the angle φ. To solve this problem a monotonic function of φ in the first and fourth quadrant, such as the sine of φ, needs to be calculated to provide a one to one mapping between the function and φ. In order to calculate $Sin(\varphi)$ it is desired to approximate the signal,

$$Y_i(t) = Im_i \cdot Sin(\omega_i t - \varphi_i) \quad (12)$$

Which is a scaled version of the derivative of Iant(t). The signal Y(t) can then be cross multiplied with Vant(t), as in equation 11, to obtain $Sin(\varphi)$. A sampled version of Y(t) can be approximated as,

$$Y_i[jTs] = C_d \cdot (Iant_i[jTs - 1] - Iant_i[jTs + 1]) \quad (13)$$

Where,

C_d – Derivative scale constant defined as,

$$C_d = \frac{1}{2 \cdot Sin(\omega_i Ts)} \quad (14)$$

The sine of φ can then be calculated from Y[jTs] in a manner similar to 11 above as,

$$\hat{Sin}(\varphi_i) = \frac{-2}{\hat{Vm}_i \cdot \hat{Im}_i \cdot k} \cdot \sum_{j=1}^{k} (Vant_i[jTs] \cdot Y_i[jTs]) \quad (15)$$

The parameters calculated in (9), (10), (11) and (15) provide the basic values required in section 2.0.

5.0 – DETERMINATION OF ANTENNA CIRCUIT STATE

5.1 – Trigger Circuit Implementation

The key to making accurate antenna system measurements using sinusoidal analysis is to determine when the antenna is in a steady state condition and then calculate the parameters Vm, Im, $Cos(\varphi)$ and $Sin(\varphi)$. In the initial implementation of the AMOS system a trigger circuit, which determines when the antenna circuit is in this steady state condition, was designed and built. This trigger circuit consists of a frequency discriminator and timer which operates by converting the modulated voltage signal Vant to a baseband binary signal that represents the high or low frequency of the modulation. For FSK signals this represents a direct demodulation of the modulated signal and for MSK it represents a binary function of the baseband signal. Each time the baseband signal changes, a countdown timer is started and begins counting down a predetermined count time referred to as the settling time. The settling time is the time required for the antenna circuit to reach a steady state condition after a frequency transition in the voltage signal. This settling time is a function of the Rg, Cas, and Las values of the antenna system and needs to be calculated in advance of AMOS installation. After the countdown timer is started, it will count down the preset settling time and output a trigger pulse which causes voltage, current, and phase measurements to be taken. If a frequency transition takes place before the settling time elapses, the timer is reset and begins the countdown again. Therefore, the function of the trigger circuit is to output a trigger pulse which will start the sampling of the voltage and current waveforms each time the antenna circuit reaches a steady state condition after a frequency transition.

5.2 – Statistical Implementation

We define a measurement as one set of Vm, Im, $Cos(\varphi)$, and $Sin(\varphi)$ values calculated from a block of samples as described in section 4.0. From a study of algorithms (9) through (15), if the voltage and current signals are highly oversampled and the calculations are made over a small number of cycles of the sampled signal, the instantaneous phase angle will be accurate even during a transition in frequency of the modulated signal. Hence, if a modulated signal is sampled at random times, rather than when in a steady state condition as described in section 5.1, the measured phase angle will be a random variable with a density function bounded by the steady state phase angles which occur at the two shift frequencies. The nature of the density function of the phase angle depends on the Q of the antenna circuit. A plot of a phase angle density function for a hypothetical LF antenna system with Rg of 1.0 ohms, Cas of 10 nanofarads, and Las of 1.013 millihenries operating at a center frequency of 50 KHz, shift frequencies of +/– 50 Hz, and baud rate of 100 is shown below in figure 2. The statistical properties of the phase angle suggest an alternate approach to determining antenna circuit state indirectly. Taking a sufficiently large block of measurements we can employ a sorting algorithm to determine the high and low phase values for each block and then calculate the desired parameters at the high and low phase values. A simple sorting algorithm which takes a block of measurements and selects the high and low phase value measurements as the high and low frequency measurements respectively works well because the phase angle φ is a monotonically increasing function of frequency. A plot of φ vs frequency for the LF system described above is shown in figure 3 with the high and low shift frequencies indicated by dashed lines. The AMOS system uses this method of sampling and sorting the values to calculate Rg, X, Cas, Las, and any other desired values and then repeats the procedure as frequently as desired.

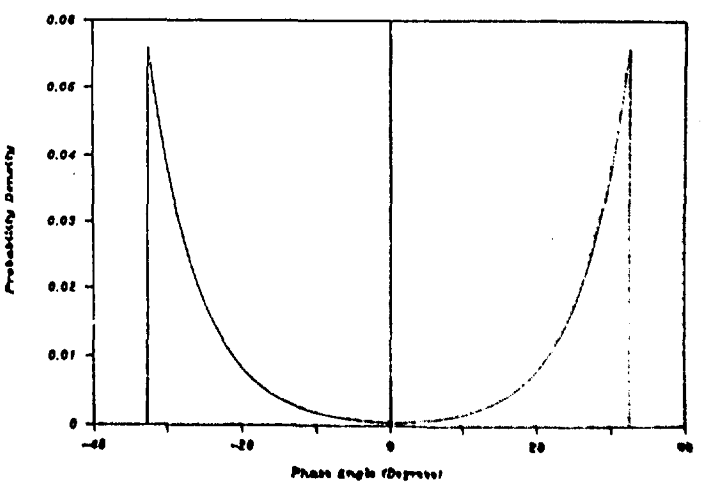

Figure 2 – Phase Density Function

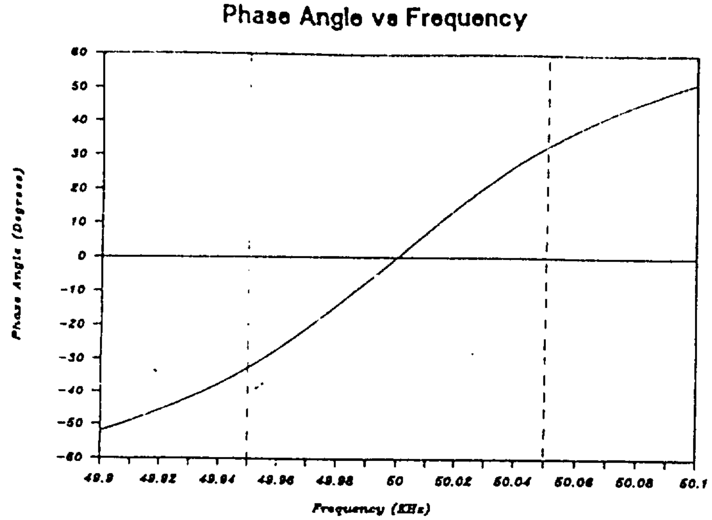

Figure 3 – Impedance Phase vs Frequency

6.0 SYSTEM IMPLEMENTATION AND CAPABILITIES

6.1 – System Hardware

The AMOS system is designed to use as much off the shelf hardware as possible to simplify complexity and minimize maintenance costs. The initial implementation of the system consisted of a commercially available personal computer, analog to digital converter, inductive current probe, capacitive voltage probe, and a trigger circuit designed and built by engineers at the Naval Ocean Systems Center (NOSC). During initial testing, stability problems were found with the trigger circuit so the AMOS was changed to remove it. After the trigger circuit (as described in section 5.1) was removed, the statistical implementation (as described in section 5.2) replaced it. In addition, a resistive voltage divider was designed and built by NOSC engineers to replace the capacitive divider which was also problematic. After initial testing a remote monitoring capability was added by installing a modem and modem software in the AMOS personal computer which allows access to the computer from any location with a standard phone line, modem, and personal computer.

6.2 – System Software

The personal computer is the heart of the AMOS and controls overall operation of all AMOS components and functions. A master program was written by the author which runs the personal computer and performs directly the calculations described in equations (9), (10), (11), (13), (14), and (15). Operation of the master program begins with downloading of user selectable operating parameters from an external data storage file. After downloading the external operational data the program goes into a data collection and storage loop. In this mode the program performs a continuous loop of 1) sampling the voltage and current signals from the respective sensors, 2) downloading data from the analog to digital converter after sampling is completed, 4) processing the data to extract Vm, Im, Cos(φ), and Sin(φ), 5) repeating steps 1 and 2 until a large enough block of data is taken to get good measurements of the high and low frequency values, 6) sorting the block and discarding all data except the high and low frequency values, 7) storing and displaying the high and low frequency values, 8) waiting a preselected amount of delay time, 9) repeating steps 1 to 8.

6.3 – Performance

On the initial testing of the AMOS, which has been done on LF sites with frequencies in the range of 50 to 60 KHz, a sampling rate of 10 MHz has been used for the modulated voltage and current signals. The sample sizes were selected to span 2 complete cycles of the voltage and current waveforms which result in sample sizes of 300 and 400 samples per measurement. Using an 8 MHz 80286 based personal computer with a sample block size of 20 measurements, high and low frequency parameters can be calculated as frequently as every 30 seconds. With a faster computer such as a 30 MHz 80386 machine, high and low frequency parameters can be calculated as fast as once a second.

7.0 – RESULTS FROM INITIAL TESTING

Initial testing of the AMOS system is currently being done at several LF transmit sites. The data presented below has been collected from these tests.

Figures 4, 5, and 6 show plots of the fundamental parameters of antenna voltage, current, and phase angle as a function of time. High and low frequency values were taken at 1 minute intervals over a 1 day time period and the data has been filtered using a second order lowpass smoothing filter.

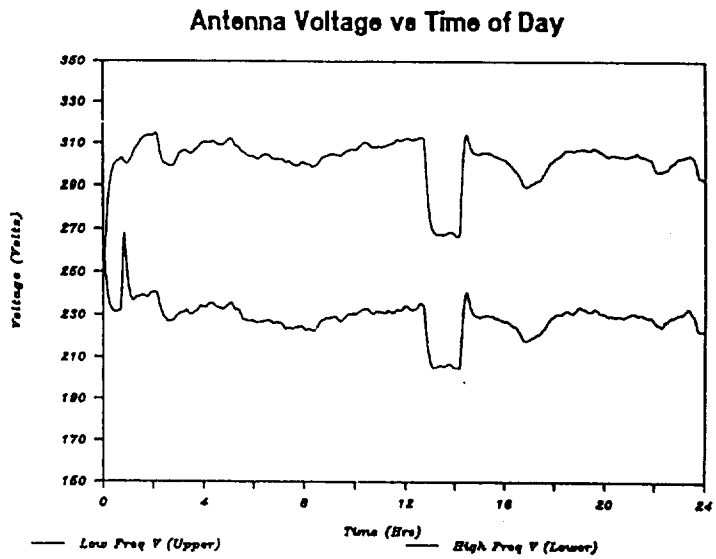

Figure 4 – Antenna Voltage vs Time of Day

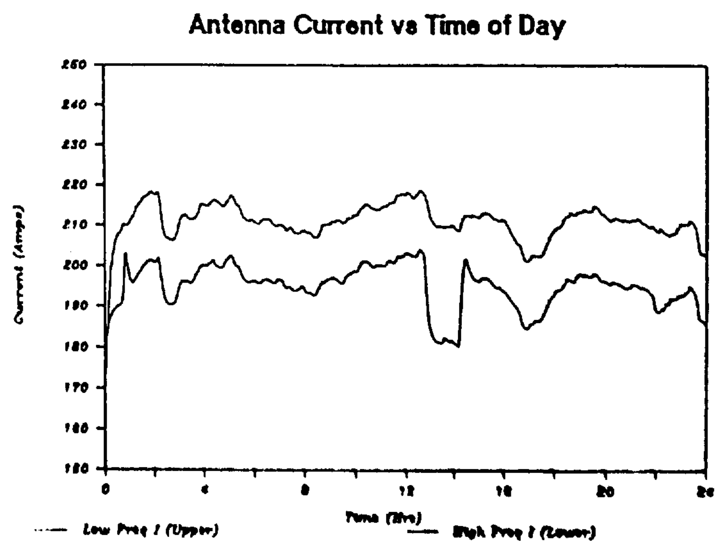

Figure 5 – Antenna Current vs Time of Day

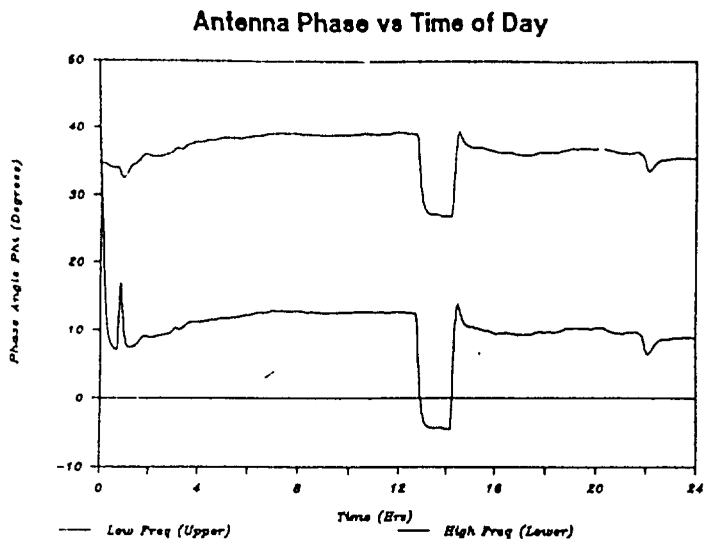

Figure 6 – Antenna Phase vs Time of Day

Figure 7 below shows the antenna gross resistance Rg vs time of day, one of the many possible antenna parameters that can be calculated from the 3 fundamental parameters shown in figures 4, 5, and 6.

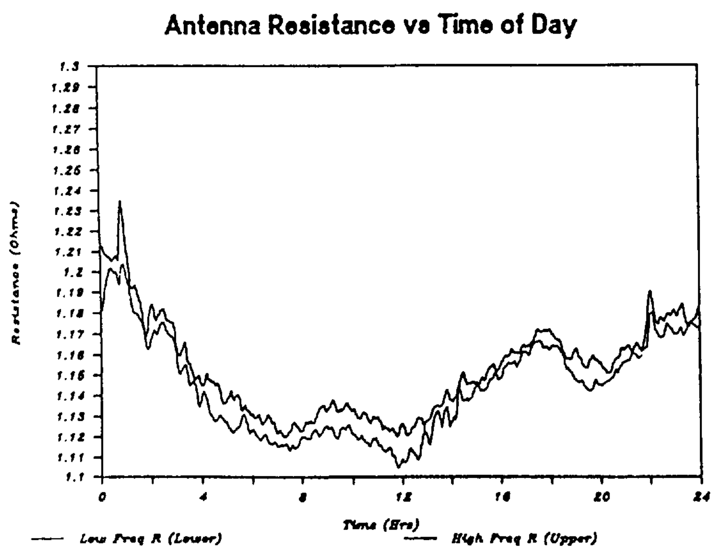

Figure 7 – Antenna Resistance vs Time of Day

Plots 4 through 7 demonstrate some of the important uses of the AMOS system. Plots 4,5, and 6 show an antenna mistuning at approximately 13:00 which lasted for about an hour. During this mistuning, output power dropped by over 1 dB. Plot 5 gives a good indication of output power at the high and low frequencies since output power is directly proportional to antenna current. Plot 7 shows the variation in gross resistance over the course of a day. In this example the gross resistance varies by approximately 10 percent. This variation could be due to changes in ground or air conductivity, moisture, or other environmental conditions. Weather induced problems have been diagnosed with the AMOS system by correlating changes in Rg with local humidity and rainfall.

Another important feature of the AMOS system is that a permanent record of antenna operating conditions and output levels can easily be saved. This can be used later to examine long term changes in the antenna system.

Further applications of the AMOS system are being developed at this time. Two units have been installed at LF antenna sites and plans are being made for the installion of several more units. A system which measures and stores a variety of weather and environmental conditions in conjunction with the antenna parameters is being integrated into the AMOS system and the software is being expanded to allow for collection and storage of this additional data. Longer term variations in antenna system parameters will be observed as more data from the existing sites is collected and studies of long term antenna system performance will be made from this data. In addition, the AMOS system is being used as the basis for the development of a comprehensive automatic antenna control and monitoring system which will help to automate transmit system operation. This will be done by using the AMOS system data to provide a tuning reference signal to drive a tuning variometer in response to changes in the antenna system.

SUMMARY

A system for measuring, displaying, and storing important antenna parameters and operating values for very low frequency (VLF) and low frequency (LF) transmit antenna systems in near real time has been developed by engineers at NOSC. The system makes antenna measurements by sampling and processing antenna voltage and current waveforms and processing the sampled signals to obtain the voltage, current, and phase angle between the two at the two antenna system shift frequencies. The processed measurement values are then displayed on a personal computer screen and stored on a floppy disk for later analysis. The system can be accessed remotely using a phone modem and data can be displayed and downloaded from the computer over ordinary phone lines. Initial testing of the system at two LF transmit antenna facilities is underway and data from the two sites is currently being analyzed to help improve antenna system operation and diagnose problems. In addition, further applications of the system are being developed including integration of a weather data collection system.

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